



**AFRL-AFOSR-VA-TR-2017-0033**

---

## Quantum Manybody Physics with Rydberg Polaritons

**Jonathan Simon  
UNIVERSITY OF CHICAGO THE  
5801 S ELLIS AVE  
CHICAGO, IL 606375418**

---

**02/07/2017  
Final Report**

**DISTRIBUTION A: Distribution approved for public release.**

Air Force Research Laboratory  
AF Office Of Scientific Research (AFOSR)/RTB1

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.</b></p>						
1. REPORT DATE (DD-MM-YYYY) 22-06-2016		2. REPORT TYPE Final			3. DATES COVERED (From - To) 03-27-2013 - 03-31-2016	
4. TITLE AND SUBTITLE Quantum Manybody Physics with Rydberg Polaritons				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER FA9550-13-1-0166		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Simon, Jonathan				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The University of Chicago 5801 South Ellis Avenue Chicago, IL 60637-5418					8. PERFORMING ORGANIZATION REPORT NUMBER  5-28333	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) USAF, AFRL AF Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203					10. SPONSOR/MONITOR'S ACRONYM(S)  USAF,AFRL	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION A: Distribution approved for public release.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT <p>Over the course of this award, an apparatus for studying a new type of synthetic material was designed, built, and tested, and a complete framework for engineering Hamiltonians developed. We built a machine capable of laser cooling 87Rb atoms, loading them into an optical lattice, and transporting them into a high-finesse, near-degenerate optical resonator, where they are dressed with a blue laser field, and Rydberg polaritonic physics may be explored. We experimentally demonstrated that photonic Landau levels could be generated for bulk photonic systems by employing a twisted resonator geometry, and that the physics of these photons could be explored on the surface of a cone. Furthermore, we exhaustively explored the physics and coherence of individual Rydberg polaritons. Along the way, we developed a novel FPGA-based feedback controller capable of control far beyond the PID regime, and employed it to enhance the feedback bandwidth in our experimental cavity lock by a factor of ten.</p>						
15. SUBJECT TERMS <p>Rydberg polariton, topological physics, manybody physics, atomic physics, cold atoms, cavity QED, FPGA</p>						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Julia F. Stewart	
U	U	U	UU		19b. TELEPHONE NUMBER (Include area code) 973.656.9062	

## INSTRUCTIONS FOR COMPLETING SF 298

**1. REPORT DATE.** Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

**2. REPORT TYPE.** State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

**3. DATES COVERED.** Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

**4. TITLE.** Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

**5a. CONTRACT NUMBER.** Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

**5b. GRANT NUMBER.** Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

**5c. PROGRAM ELEMENT NUMBER.** Enter all program element numbers as they appear in the report, e.g. 61101A.

**5d. PROJECT NUMBER.** Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

**5e. TASK NUMBER.** Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

**5f. WORK UNIT NUMBER.** Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

**6. AUTHOR(S).** Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES).** Self-explanatory.

**8. PERFORMING ORGANIZATION REPORT NUMBER.**

Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES).** Enter the name and address of the organization(s) financially responsible for and monitoring the work.

**10. SPONSOR/MONITOR'S ACRONYM(S).** Enter, if available, e.g. BRL, ARDEC, NADC.

**11. SPONSOR/MONITOR'S REPORT NUMBER(S).** Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

**12. DISTRIBUTION/AVAILABILITY STATEMENT.** Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

**13. SUPPLEMENTARY NOTES.** Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

**14. ABSTRACT.** A brief (approximately 200 words) factual summary of the most significant information.

**15. SUBJECT TERMS.** Key words or phrases identifying major concepts in the report.

**16. SECURITY CLASSIFICATION.** Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

**17. LIMITATION OF ABSTRACT.** This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

**Title:** Quantum Manybody Physics with Rydberg Polaritons

***AFOSR AWARD#:*** FA9550-13-1-0166

***Recipient:*** University of Chicago  
5801 South Ellis Avenue  
Chicago, Illinois 60637-5418

***Principal Investigator:*** Jonathan Simon  
Neubauer Family Assistant Professor of Physics  
929 East 57<sup>th</sup> Street GCIS E207  
Chicago, Illinois 60637  
773.702.9661  
[simonjon@uchicago.edu](mailto:simonjon@uchicago.edu)

Atomic and Molecular Physics  
**Tatjana Curcic**, Program Manager

***REPORT DATE:*** 6/22/2016

***REPORT PERIOD:*** 3/27/2013-3/31/2016

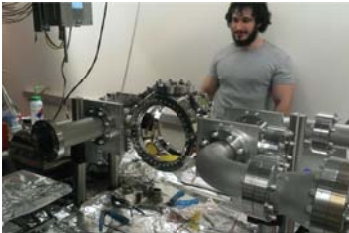
## Abstract

Over the course of this grant, we have seen tremendous progress, both theoretically and experimentally, in our control of photonic Hamiltonians. We have developed near-degenerate optical resonators to manipulate the single-particle sector, and coupled the photons in these resonators to small, optically thick samples of Rubidium Rydberg atoms to eventually mediate strong photon-photon interactions and build photonic materials.

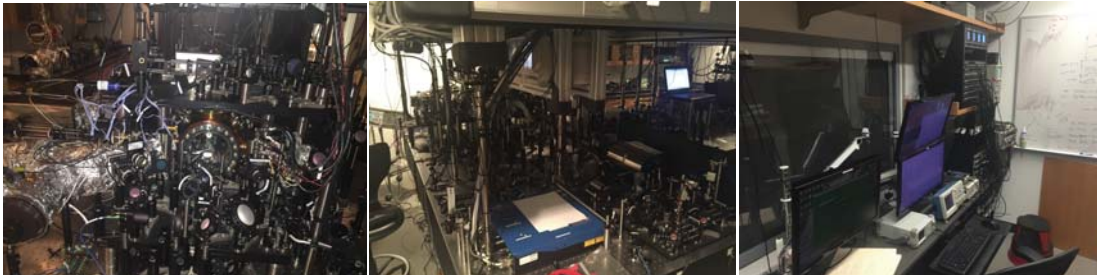
This document summarizes these various efforts, and progress towards achieving the listed scientific goals. In short, we have built a one-of-a-kind apparatus to laser-cool  $^{87}\text{Rb}$  atoms, load them into an optical lattice, and transport them, within  $\sim 10\text{ms}$ ,  $2\text{cm}$  into the small ( $12\text{ }\mu\text{m}$ ) waist of a running-wave optical resonator. The atoms are then Rydberg-dressed with a narrow laser at  $480\text{nm}$ , and the structure of the resulting cavity-polaritons is spectroscopically probed. We find that the individual cavity-Rydberg-polaritons behave in quantitative agreement with models that we have developed. In conjunction with synthetic magnetic fields generated through non-planar cavities, we are now poised to explore fractional quantum hall physics of photonic quasi particles.

Our approach to engineering photonic materials relies heavily on coupling our photons to *both* Rydberg atoms to mediate interactions, and a high-finesse optical resonator to control the single particle properties (Sommer *et al.*, *NJP* 18, 035008, 2016). This combination has proven unexpectedly challenging, as the cavity structure produces stray fields which perturb the Rydberg atoms very strongly. As such, a large portion of this document is dedicated to exploring these effects, and the final solution which we have ultimately reached, based on an even more exotic type of optical resonator, to keep the resonator mirrors as far as possible from the atomic sample.

## Apparatus



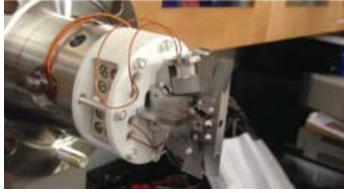
Over the course of the grant, we have built a cold atom machine combining the challenges of Rydberg physics with the challenges of cavity quantum electrodynamics. The apparatus, shown in multiple stages of construction at left and below, spans three optical tables in two rooms: One for the experimental control system, comprised of two computers, that control sequenced 32 analog outputs, 32 digital outputs,  $12 \times 3.5\text{GHz}$  FPGA-controlled DDS channels,  $4 \times 500\text{MHz}$  static DDS channels, and a four-channel FPGA-based pulse timer.



The optical setup is split into two tables: one for laser preparation, and one (primarily) for the vacuum system. On the laser table, reference, MOT, and Repumper DFB lasers are frequency stabilized, with agile, real-time control of their wavelength across the  $^{87}\text{Rb}$  D2 line. The MOT laser is amplified with a fiber-coupled tapered amplifier, and combined with the Repumper laser, to generate the magneto-optical trap. The remainder of this table is employed for a  $783\text{nm}$  near-

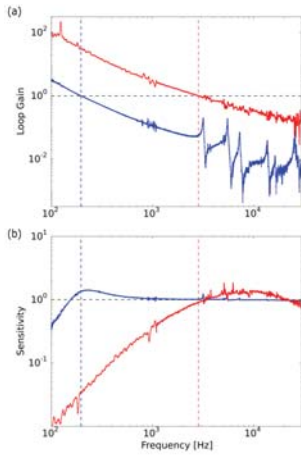
detuned transport lattice laser, generated from an electronically narrowed DFB sent through a tapered amplifier, as well as a 1560nm fiber laser employed for cavity locking with a few kHz linewidth, which is fiber-amplified, and single-pass-doubled to provide our ultra-narrow probe laser for Rydberg EIT experiments. The 480nm laser for exciting from the P-state to the Rydberg state is housed on the second optical table, along with an ultrastable vacuum cavity employed to lock it, and the 1560nm fiber laser. We employ a novel sideband-on-sideband laser locking scheme to achieve agile control of the experimental cavity wavelength, along with the probe and cavity locking lasers.

The heart of the apparatus is the optical resonator which resides within a UHV chamber. Because our experiments occur on millisecond timescales rather than the second timescales of a typical lattice experiment (the photons move a lot faster than atoms tunnel), we are able to get away with a vacuum of only  $\sim 10^{-9}$  Torr (background-gas limited lifetime of  $\sim 2$  sec), permitting a much

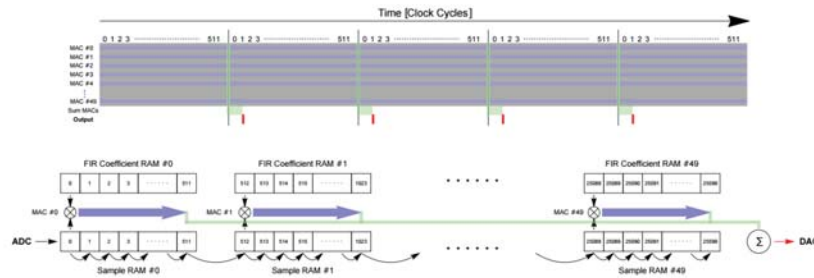


wider array of materials in our vacuum chamber than ultracold-atom/lattice experiments. This has enabled us to employ exotic resonators relying upon numerous in-vacuum electrodes, heating elements, and piezo-electric transducers. While the cavity has now undergone several iterations, its qualitative form is shown at left, immediately prior to installation into the vacuum system.

To stabilize this resonator, we employ a electro-optic sideband FM transmission lock, similar in spirit to the Pound-Drever-Hall scheme. This approach, while successful, has suffered from the mechanical floppiness of our optical resonator mounting structure. Such floppiness (low frequency mechanical resonances) is unavoidable in exotic resonator geometries, and will need to be resolved in the long-term. To this end, we have developed a state-of-the-art FPGA-based finite-impulse-response filter to precisely electronically cancel mount resonances up to  $\sim 100$  kHz. This first-of-its-kind device performs a 60000 point fixed-point convolution 250000 times per second, employing 50 parallel multiply-and-accumulate channels each operating at over 100 MHz



(as shown below right). The results of employing this device, shown at left, are striking. The mechanical resonances and anti-resonances in the piezo transfer function have been completely cancelled out up to 100 kHz, enabling a factor of ten increase in noise suppression bandwidth. This technique promises to be extremely useful for rapidly switching



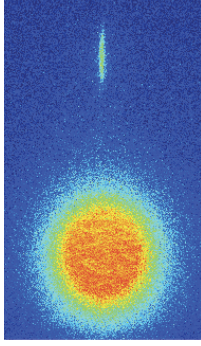
the resonant frequency, as well as stabilization of higher finesse cavities, more rapid turn-off of the MOT coils (which otherwise induce eddy currents in the piezos and shake the resonator). It appears likely that the technology will also find application in LIGO, as well as optomechanical squeezing experiments.



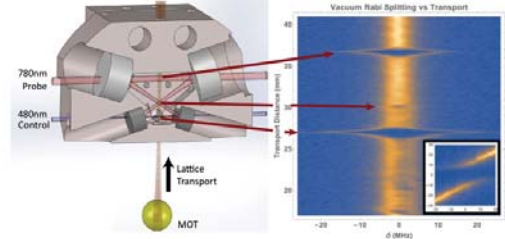
## Towards Manybody Physics with Rydberg Polaritons

Over the course of the grant, we have succeeded in exploring the properties of cavity Rydberg polaritons, and along the way have learned quite a bit about stray electric fields and their impact upon Rydbergs.

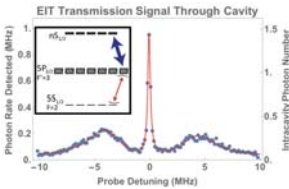
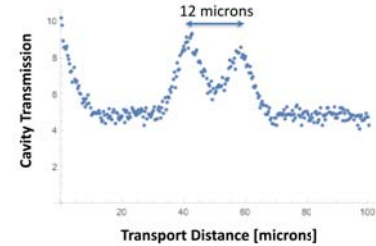
The first step in our experiments is to load a MOT, and polarization gradient cool it, and load it into an optical transport lattice. In the fluorescence image at left, only a small fraction of the atoms (upper pencil-shaped cloud) are loaded into our transport lattice. The majority remain in the MOT (large, bright disk). We have since loaded our lattice at densities beyond  $10^{10}/\text{cm}^3$ , capturing nearly half of our MOT.



We then adiabatically transport the atoms into the optical resonator by ramping (via DDS) the relative frequency of the lattice beams. In the figure below right, the cavity transmission is plotted versus probe frequency (x-axis) and atom transport distance (y axis). The appearance of an atomic vacuum Rabi splitting at 27mm of transport and 36mm of transport reveals the presence of the atomic cloud in the lower- and upper- waists of our optical resonator, respectively. The inset reveals the avoided crossing when the cavity and probe are tuned.

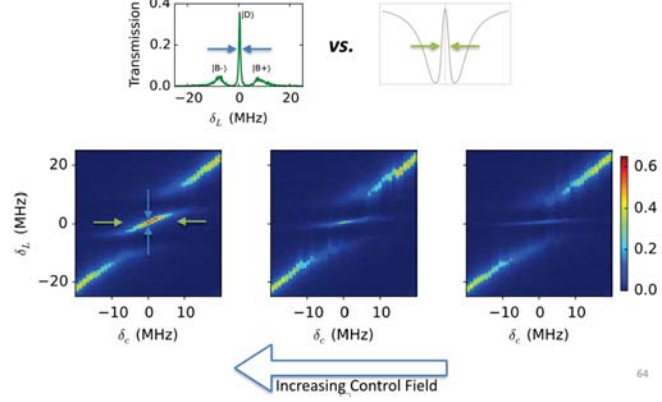


To mediate interactions between the photons, it will eventually be essential that the polaritonic quasi-particles are localized to distances where their Rydberg components can interact substantially. For  $n=70\sim 100$  Rydbergs, an interaction of a few MHz requires separations less than approximately 10 microns. Our first experiments treat a single-mode resonator as a sort of polaritonic “quantum dot” that photons can tunnel into and out of, and so the size of this island should be of order 10 microns. We achieve this, first and foremost, by employing a resonator whose designed mode-waist is 12 microns. We verify experimentally that the waist is 12 microns by blowing away atoms by sending light through the resonators TEM<sub>10</sub> mode, thus imprinting the inverse of the shape of the TEM<sub>10</sub> mode on the atomic cloud. We then transport the atoms through the cavity (using the lattice) and observe the transmission as a function of location. As the atoms detune the resonator, the shape of the TEM<sub>10</sub> mode is apparent in the transmission spectrum, as shown at right.

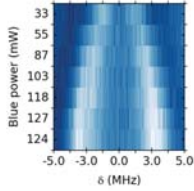


We next explored Rydberg EIT in the single-mode case by dressing the atomic cloud in the lower waist with a 480nm laser field, tuned to the 5P-nS transition, where  $n$  is 40~68. A typical probe scan, shown at left, reveals the vacuum Rabi doublet characteristic of a medium resonantly coupled to an optical cavity, as well as a dark resonance characteristic of an ensemble of three-level emitters. This dark resonance may be narrower than the optical resonator itself, as it is largely Rydberg-like, and the atomic Rydberg state can live longer than the resonator photons (Ningyuan *et al.*, **PRA** 93, 041802, 2016).

The narrowing of the resonator line due to the coupling to the Rydbergs is characteristic of a *dynamical slowdown* of polaritonic dynamics, relative to their photonic counterparts. It is also manifest as a reduced sensitivity to the resonator frequency, and most broadly reflects a compression of the single particle spectrum of the polaritons compared with the photons. We explore this first with a single isolated cavity mode, by mimicking the different frequencies of different modes by detuning the cavity, at right. It is apparent that, as the control field is reduced, the EIT feature becomes spectrally narrower, and its dependence upon the resonator frequency,  $\delta_c$ , is reduced. One might be inclined to associate the width of the EIT feature with the width of the free-space EIT window; this is a false equivalence, as the width of the EIT feature has more to do with how long the photon lives in the cavity, than the spectral range over which EIT persists. Indeed, width of the free-space (corrected for the cavity-finesse-enhancement to the OD) is *precisely reflected* in the range of resonator frequencies over which the polariton lifetime is not reduced.

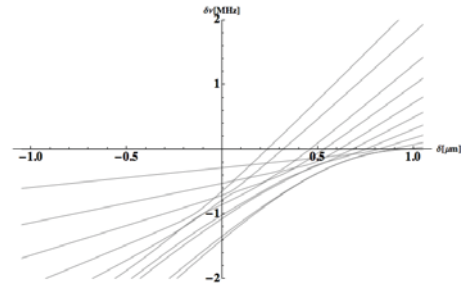


To explore the dynamical slowdown effect more thoroughly, we engineered our resonator to have manifolds of modes which are nearly degenerate, given by  $\text{TEM}_{(n,0)}$  and  $\text{TEM}_{(0,2n)}$ . In the figure at right, we explore the spectrum of  $\text{TEM}_{10}$  and  $\text{TEM}_{02}$  dark polariton modes, as the blue control field power is reduced; we observe the expected mode compression. This indicates that once we have a cavity with a larger degenerate manifold of modes, reflecting the physics of either a massive harmonically trapped particle, a particle in a magnetic field, or a particle on a curved surface, the mode compression will behave as our simple theoretical models predict.



Quite recently, we managed to create a degenerate, twisted optical resonator within which photons behave as massive particles in a synthetic magnetic field (“Synthetic Landau levels for photons”, Schine *et al.*, **Nature** 2016: doi:10.1038/nature17943). This groundbreaking result is the first demonstration of a bulk magnetic field for optical photons, all prior work having been conducted in a lattice. Furthermore, it is completely consistent with the requirements for introducing strong Rydberg-EIT based photon-photon interactions, for exploration of FQH/Laughlin physics, and the properties of anyonic quasi-particles.

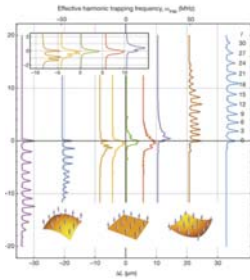
Perhaps most importantly, we have demonstrated that as we tune the resonator to precisely cancel the harmonic confinement induced by the resonator twist, the massively degenerate lowest Landau level that we produce is *exquisitely* flat. Consistent with modeling performed for the initial grant proposal (see right), we observe more than 10 states in the LLL compressed into a few MHz of bandwidth (see below), less than the bandwidth of the typical EIT window for our cavity-enhanced OD. Equally important is that Laughlin states



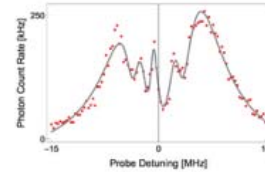
*remain* nearly-zero energy states, *even in the presence of strong interactions*. This should be contrasted with crystalline states, whose interaction energy scales strongly with system size



(particularly for a harmonically trapped crystal). This means that photonic Laughlin states will be less constrained by the EIT width than crystalline states, and should be easier to produce, more robustly.



The next step, then, is to explore interactions between polaritons. To this end, we have begun attempting to operate at higher principal quantum numbers for the Rydberg state, where the interactions between the atoms becomes stronger. What we have found is that stray electric fields become prohibitive before the interactions between the atoms are strong enough to observe in the optical field. Initially, we contended with a constant offset field of  $\sim 0.5\text{V/cm}$ , induced by a metal electric field filter placed next to the atoms to shield them from charges built up on the dielectric mirrors. As best we can tell, this field arises from Rubidium atoms adsorbed onto the metallic surface forming patches of electric dipoles. We observed this field first as an EIT-splitting of Rydberg D-states (see right).



To compensate this offset field, we moved from a resonator with only a passive electric field *filter* (see below, left), to one with 8 segmented electrodes (see below, second from left). This enabled us to compensate for stray fields, but still left us with large gradients and field curvatures that, while perhaps possible to correct in principle, in practice we were unable to control before they drifted due to additional Rubidium deposition.

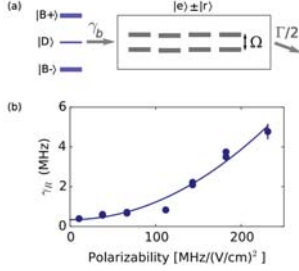


Moving forward, we have designed and built an exotic resonator employing both convex *and* concave supermirrors, exhibiting a similarly small  $\sim 12$  micron waist, but with the closest surface nearly a cm from the atomic cloud, rather than a mm (see above, second from right). In conjunction with a re-orientation of our atomic source to prevent line-of-site access to the metal structure, we anticipate 1000x suppression of stray fields, and 10000x suppression of gradients, and 100000x suppression of field curvature. In truth, so long as the fields are stable, even a 10x suppression in the fields, and corresponding suppression in gradients and curvatures, will be more than sufficient to perform all desired experiments up to  $n=100\text{S}$ .

In parallel, we have begun to develop a UHV-compatible twisted resonator whose length is broadly tunable with slip-stick piezo actuators (see above, right). This resonator *also* boasts a minimum separation between atoms and all resonator structures of nearly a cm, relying again upon convex supermirrors.

In keeping with our initial proposal, we have also explored the collective suppression of inhomogeneous broadening in cavity EIT. This is important because, to lowest order, it is in fact electric field *gradients* and *curvature* which decohere Rydberg polaritons, and not the

constant offset field, which simply shifts the polariton resonance, and in any event may be compensated. In the initial grant proposal, we anticipated that the dominant source of inhomogeneous broadening would be atomic motion (so-called *Doppler broadening*), arising from the k-vector mismatch between cavity photon (at 780nm) and control field (at 480nm). Fascinatingly, this broadening mechanism takes the same form as that arising from inhomogeneous electric fields:



Shown at left is the extracted decay rate of the collective Rydberg excitation, as a function of its polarizability (adjusted by changing principal quantum number). While the single particle inhomogeneous linewidth scales linearly with the polarizability of the Rydberg state, the observed broadening scales quadratically. This indicates that there is in fact a detuning between the inhomogeneously broadened manifold of single particle states, and the cavity polariton state of interest.

As mentioned above, this was anticipated in the original grant proposal, arising from the absence of a cavity coupling of the broadened single particle states. The demonstrated existence of this suppression is fantastic news for our next generation of experiments, indicating that not only will we be insensitive to doppler broadening, but a modest improvement in stray fields will lead to a marked improvement in polariton coherence.

1.

**1. Report Type**

Final Report

**Primary Contact E-mail****Contact email if there is a problem with the report.**

simonjon@uchicago.edu

**Primary Contact Phone Number****Contact phone number if there is a problem with the report**

7737029661

**Organization / Institution name**

University of Chicago

**Grant/Contract Title****The full title of the funded effort.**

Quantum Manybody Physics with Rydberg Polaritons

**Grant/Contract Number****AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".**

FA9550-13-1-0166

**Principal Investigator Name****The full name of the principal investigator on the grant or contract.**

Jonathan Simon

**Program Manager****The AFOSR Program Manager currently assigned to the award**

Tatjana Curcic

**Reporting Period Start Date**

3/27/2013

**Reporting Period End Date**

3/31/2016

**Abstract**

Over the course of this award, an apparatus for studying a new type of synthetic material was designed, built, and tested, and a complete framework for engineering Hamiltonians developed. We built a machine capable of laser cooling 87Rb atoms, loading them into an optical lattice, and transporting them into a high-finesse, near-degenerate optical resonator, where they are dressed with a blue laser field, and Rydberg polaritonic physics may be explored. We experimentally demonstrated that photonic Landau levels could be generated for bulk photonic systems by employing a twisted resonator geometry, and that the physics of these photons could be explored on the surface of a cone. Furthermore, we exhaustively explored the physics and coherence of individual Rydberg polaritons. Along the way, we developed a novel FPGA-based feedback controller capable of control far beyond the PID regime, and employed it to enhance the feedback bandwidth in our experimental cavity lock by a factor of ten.

**Distribution Statement****This is block 12 on the SF298 form.**

Distribution A - Approved for Public Release

**Explanation for Distribution Statement****If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.**

DISTRIBUTION A: Distribution approved for public release.

## SF298 Form

Please attach your [SF298](#) form. A blank SF298 can be found [here](#). Please do not password protect or secure the PDF. The maximum file size for an SF298 is 50MB.

[SF298 form D1.pdf](#)

**Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF. The maximum file size for the Report Document is 50MB.**

[FinalReport.pdf](#)

**Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.**

### **Archival Publications (published) during reporting period:**

"Synthetic Landau Levels for Photons," Schine et al., Nature 2016. doi:10.1038/nature17943 .

"Observation and characterization of cavity Rydberg polaritons," Ningyuan et al., Physical Review A 93 (4), 041802.

"Engineering photonic Floquet Hamiltonians through Fabry–Pérot resonators," Sommer et al., New Journal of Physics 18 (3), 035008.

"Active Cancellation of Acoustical Resonances with an FPGA FIR Filter," Ryou et al., arXiv:1604.04668.

"Time-and site-resolved dynamics in a topological circuit," Ningyuan et al., Physical Review X 5 (2), 021031.

"Quantum Crystals and Laughlin Droplets of Cavity Rydberg Polaritons", Sommer et al., arXiv preprint arXiv:1506.00341.

"Engineering topological materials in microwave cavity arrays," Anderson et al., arXiv preprint arXiv:1605.03177.

### **2. New discoveries, inventions, or patent disclosures:**

**Do you have any discoveries, inventions, or patent disclosures to report for this period?**

No

**Please describe and include any notable dates**

**Do you plan to pursue a claim for personal or organizational intellectual property?**

**Changes in research objectives (if any):**

**Change in AFOSR Program Manager, if any:**

**Extensions granted or milestones slipped, if any:**

**AFOSR LRIR Number**

**LRIR Title**

**Reporting Period**

**Laboratory Task Manager**

**Program Officer**

**Research Objectives**

**Technical Summary**

**Funding Summary by Cost Category (by FY, \$K)**

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

#### **Report Document**

#### **Report Document - Text Analysis**

#### **Report Document - Text Analysis**

#### **Appendix Documents**

## **2. Thank You**

#### **E-mail user**

Jun 23, 2016 11:12:14 Success: Email Sent to: simonjon@uchicago.edu